University of Glasgow

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Introduction: The promises of gravitational-wave astronomy

Iain W Martin, Nils Andersson, Jim Hough, Carole Mundell

In 2015, the first direct detection of gravitational waves was made by the Advanced LIGO detectors [1]. The signal observed originated from a binary black hole system, approximately 410 Mpc away from Earth, in which two black holes of 36 and 29 solar masses spiralled into each other and merged to form a single black hole of 62 solar masses, radiating about 3 solar masses of energy as gravitational waves. This detection was recognised by the award of the 2017 Nobel Prize in Physics.

Following the first detection, four more black hole mergers have been observed [2-4]. In addition, a binary neutron star inspiral has been observed [5]: this event has been associated with a gamma ray burst detected 1.7 seconds after the gravitational wave event occurred [6-8]. Follow-up electromagnetic observations have identified a counterpart source close to the galaxy NGC 4993 which is consistent with the position and distance obtained from the gravitational wave data [9-11]. An extraordinary amount of analysis has been carried out based on these detections, including a new measurement of the Hubble constant [12] based on the neutron star inspiral, while the black hole observations have confirmed the existence of stellar black holes in a mass range never before observed. These are just some examples of the power and promise of gravitational-wave astronomy.

The ability to directly detect gravitational waves is the result of several decades of experimental work. Efforts began in the 1960s with the construction of detectors consisting of large aluminium bars. The passage of a gravitational wave was expected excite the fundamental resonant mode of the bar, which would be measured by piezo-electric sensors. This technique is only sensitive at frequencies around the fundamental resonant frequencies of the bars, and to obtain high sensitivity over a broader frequency band, interferometric detectors were developed.

These detectors are based on the Michelson interferometer, and monitor the relative separation of mirrors located at the end of km-scale perpendicular arms. Incoming laser light is directed along each arm by a beam-splitter, and reflected from mirrors at the end of the arms. The reflected light recombines at the beam-splitter, creating an interference pattern at the output of the interferometer. Any changes in the position of the mirrors will produce a change in the interference pattern at the output of the detector. The change in arm-length produced by a gravitational wave is very small. In the case of the first detection, the peak change in length measured was 4×10^{-18} m. Reaching the sensitivity required to detect these very small length changes is a huge technical challenge. A wide variety of noise sources must be overcome, including quantum noise associated with the laser light, seismic noise from motion of the Earth coupling into the detector and thermal noise associated with thermally induced vibrations of the interferometer mirrors.

While gravitational waves were not directly detected until 2015, there was very strong indirect evidence of their existence from measurements of the binary pulsar PSR B1913+16, which showed that it was losing energy at a rate consistent with the emission of gravitational waves [13, 14].

The initial detections were made by the two Advanced LIGO detectors (located at Hanford, Washington and Livingston, Louisiana in the USA) [15]. In August 2017 Advanced Virgo [16] (located close to Pisa in Italy) joined Advanced LIGO in an observing run, with a black hole inspiral being observed in all three instruments and a binary neutron star system being observed by both LIGO detectors while being in a null direction for the Virgo detector [4, 5]. Observations from several detectors at different locations allow more precise localisation of the source and there are plans for a world-wide network of detectors including a third Advanced LIGO detector in India and an underground, cryogenic detector called KAGRA, which is under construction in the Kamioka mine in Japan.

This issue explores a number of aspects of gravitational-wave astronomy. The article by Schutz, 'Gravitational Wave Astronomy: Delivering on the Promises' gives an overview of the current status of the field with details of the first detections of gravitational waves and the new gravitational-wave science which will be possible in the future. One important aspect discussed here is the potential of planned space-based detectors to allow observations of much lower frequency sources than can be observed by the ground-based interferometers. More details of the proposed LISA (Laser Interferometer Space Antenna) mission can be found in [17, 18].

To reach the required sensitivities for planned future detectors significant research and development of detector technologies will be required, and a number of these are discussed in the next four articles. Thermal noise associated with the highly-reflective coatings applied to the interferometer mirrors will limit the performance of current detectors at their most sensitive frequencies. Research into novel coatings to overcome this limit is discussed in 'Mirror Coatings for Gravitational Wave Detectors' by Steinlechner. Quantum mechanics sets another fundamental limit to detector sensitivity: however, techniques exist for surpassing the 'standard quantum limit', as discussed by Heurs in 'Gravitational wave detection using laser interferometry beyond the standard quantum limit'. One of the key contributions from the UK to the aLIGO detectors was the fused silica fibres used to suspend the detector mirrors. This contribution, and the development of enhanced suspensions to enable the construction of future detectors, is discussed in 'Quasi-monolithic mirror suspensions in ground-based gravitational wave detectors' by van Veggel

Gravitational wave detectors are some of the most sophisticated instruments ever constructed, and a wide variety of instrumental and environmental noise sources can affect data quality. An overview of how such transient noise sources can be identified, and their effect on data quality minimised, is given by Nutall in 'Characterising Transient Noise in the LIGO Detectors'.

We now move on to consider more details of the science which can be carried out form gravitational wave detections. In 'Gravitational waves from neutron stars and asteroseismology', Ho explores the astrophysics of neutron stars and the ways in which observations of gravitational waves from neutron stars will advance our understanding of these exotic systems. 'High energy astrophysics and the search for sources of gravitational waves' by O'Brien and Evans discusses gravitational wave emissions associated with gamma ray bursts, the most luminous sources of high-energy radiation, and describes the methods used to search for electromagnetic counterparts to such gravitational wave events.

In addition to the ground-based gravitational wave detectors, another parallel effort to detect gravitational wave sources is based on accurately timing the signals from pulsars, searching for small variations caused by gravitational waves. This method described in 'The prospects of pulsar timing with new generation radio telescopes and the SKA' by Stappers et al.

The complex challenge of developing technology and experimental techniques to enable the detection of gravitational waves has led to many applications and spin-offs in other fields. Two examples are given in articles here. The article 'Control of cell behaviour through nanovibrational stimulation – nanokicking' by Roberstson et al. focuses on a spin-off project in which stem cell differentiation is controlled by the application of nano-scale vibrations to the cells. This has potential applications in the growth of bone tissue. 'MEMS Gravimeters as a New Tool for Gravity Imaging' by Middlemiss et al. discusses the development of novel microelectromechanical system gravimeters. These small and portable devices can sensitively measure small changes in the local gravitational acceleration, with many potential application associated with mapping subterranean density including mineral exploration, archaeology, volcanology and defence.

This is a very exciting time in gravitational astronomy. After decades of challenging work, the first gravitational wave observations of black hole and neutron star inspirals have been made, providing a wealth of exciting and some unexpected results. As the sensitivity of detectors improves and the number of sources detected increases, the future promises to be even more exciting, as we enter the epoch of multi-messenger astronomy.

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